Optimization of Electrical Discharge Machining Parameters Using Genetic Algorithm Technique

Thesis submitted in partial fulfilment of the requirements for the Degree of

Bachelor of Technology (B. Tech.)

In

Mechanical Engineering

By

Lokesh Kumar Bican

Roll no. 109me0362

Department of Mechanical Engineering
National Institute of Technology, Rourkela
2013

National Institute of Technology - Rourkela

CERTIFICATE

This is to certify that the work in this thesis report entitled "**Optimization of Electrical Discharge Machining Parameters by Genetic Algorithm Technique**" submitted by **Lokesh Kumar Bican** in partial fulfilment of the requirements for the degree of Bachelor of Technology in Mechanical Engineering Session 2009-2013 in the department of Mechanical Engineering, National Institute of Technology Rourkela, is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge the matter embodied in the thesis has not been submitted to any University/Institute for the award of any Degree or Diploma.

Dr. Saroj Kumar Patel
Associate Professor
Dept. of Mechanical Engineering
National Institute of Technology
Rourkela – 769 008

Date:

Acknowledgement

It gives me immense pleasure to express my deep sense of gratitude to my supervisor Prof. Saroj Kumar Patel for his invaluable guidance, motivation, constant inspiration and above all for his ever co-operating attitude that enabled me in bringing up this thesis in the present form.

I am extremely thankful to Prof. K. P. Maity, Head, Department of Mechanical Engineering and Prof. S. K. Sahoo, Course Coordinator, for their help and advice during the course of this work.

Lokesh Kumar Bican

Roll no: 109me0362

Dept of Mechanical Engineering

National Institute Of Technology

Rourkela 769008.

CONTENTS

List of tables:

List of figures:

ABSTRACT

Productivity and quality are two important aspects have become great concerns in today's competitive global market. Every production/manufacturing unit mainly focuses on these areas in relation to the process as well as product developed. Electrical discharge machining (EDM) process, even now it is an experience process, wherein still the selected parameters are often far from the maximum, and at the same time selecting optimization parameters is costly and time consuming.

Material Removal Rate (MRR) during the process has been considered as productivity estimate with the aim to maximize it. With an intention of minimizing surface roughness is been taken as most important output parameter. These two opposite in nature requirements have been simultaneously satisfied by selecting an optimal process environment (optimal parameter setting). Objective function is obtained by Regression Analysis and Analysis of Variance. Then objective function is optimized using Genetic Algorithm technique. The model is shown to be effective; MRR and Surface Roughness improved using optimized machining parameters.

Key words: Analysis of Variance; Electrical discharge machining (EDM Material removal rate (MRR); Genetic algorithm; Surface roughness; Regression analysis.

Chapter 1

Introduction of Electrical Discharge Machining

1.1 Background of Electrical Discharge Machining

EDM machining techniques were discovered far back in the 1770_s by an English Scientist. However, this technique was not fully taken advantage until 1943 when Russian scientists learned how its erosive effects could be controlled and used for machining purposes. It was developed commercially in the mid-1980s, wire EDM made lot of change that helped shape the metal working industry we see today.

Now the now concept of manufacturing uses non-conventional energy sources like light, sound, chemical, mechanical, electrical and ions. With the technological and industrial growth, devolvement of harder machining materials, which find wide application in nuclear engineering ,aerospace and other industries owing to their high strength to weight ratio, heat resistance and hardness qualities has been witnessed New developments in the field of material science have led to new engineering metallic materials, high tech ceramics and composite materials having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity so that they can readily be machined by spark erosion. Non-traditional machining has improved out of the need to machine these alien materials. The machining processes are non-conventional in the sense that they do not employ traditional tools for metal removal and but they directly use other forms of energy. The problems of high complexity in size, shape and higher demand for product accuracy and surface finish can be solved through non-traditional methods.

EDM has been replacing grinding, milling, drilling and other traditional machining Operations and is now a well-established machining option in many manufacturing industries everywhere in the world. And is capable of machining hard material components or geometrically complex, which are precise and difficult-to-machine such as heat treated super alloys, ceramics, composites, carbides tool steels, heat resistant steels etc. being widely used in mould and die making industries, nuclear industries, aeronautics and aerospace. Electric Discharge Machining has also made its presence felt in the new fields such as medical, sports and surgical, optical, instruments, including automotive R&D areas.

1.2 Introduction of EDM

It is a non-traditional electro-thermal machining process, in which electrical energy is used to generate electrical spark and material removal occurs due to thermal energy produced by the spark.

EDM is mainly used to machine high strength temperature resistant alloys and materials difficult-to-machine. EDM can be used to machine irregular geometries in small batches or even on job-shop basis. Work material is to be electrically conductive to be machined by EDM.

1.3 EDM Principle

Due to erosion caused by rapidly recurring spark discharge that taking place between the tool and work piece metal is removed in this process. About a thin gap of .025mm is maintained between the work piece and the tool by a servo system shown in Figure1. Both work piece and tool are submerged in a dielectric fluid. EDM oil/kerosene/deionized water

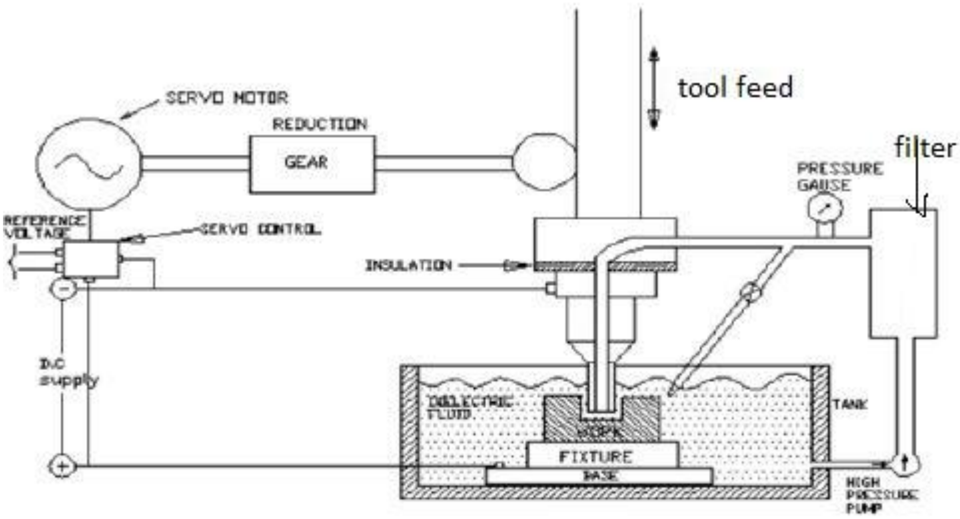
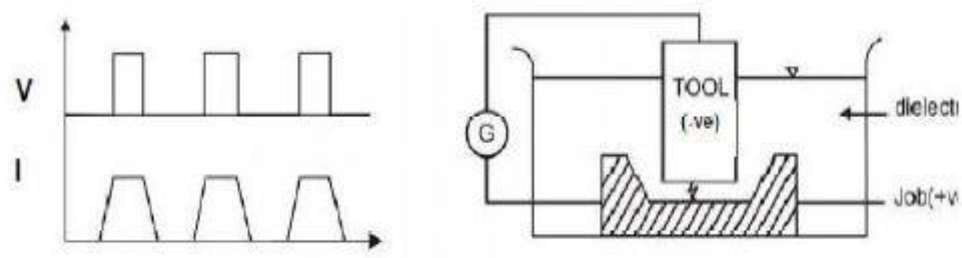


Figure 1. Electric discharge machining set up

The work piece is anode and tool is cathode. In about an interval of 10 micro seconds voltage across the gap becomes sufficiently large to discharge spark. Electrons and positive ions get accelerated, creating a discharge channel that becomes conductive. It is then at this point when the spark jumps causing collisions between electrons and ions creating a channel of plasma. Electrical resistance suddenly drops of the previous channel allows that current density reaches very high values producing an increase of ionization and the creation of a powerful magnetic field . The moment spark occurs sufficiently pressure developed between tool and work due to which high temperature is reached and then metal is eroded at that high temperature and pressure.

Material removal occurs due to such extreme localised temperature. Due to instant vaporization of the material as well as due to melting material removal occurs. Molten metal is not completely removed but only partially.



.

Figure 2.Working principle of EDM process

The plasma channel is no longer sustained as the potential difference is withdrawn as shown in Figure 2. It generates shock or pressure waves, which evacuates the molten material forming a crater of removed material all around the region of spark, as the plasma channel collapse.

1.4 EDM Based on Types

There are two types of EDM basically:

1.4.1 Die sinking EDM

1.4.2 Wire-cut EDM

1.5 EDM Parameters

(a) Spark On-time (pulse time or T_{on}): It is the duration of the time (µs) that current is allowed to flow per cycle. MRR varies directly proportional to the amount of energy applied during this on-time. This energy is really controlled by the peak current and length of the on-time.

(b) Spark off time (pause time or T_{off}):

Here, this time allows the molten material in getting solidified and to be wash out of the arc gap. This parameter affects the speed and the stability of the cut. Thus, if the off-time is too short, it creates an unstable spark.

(c) Arc gap (or gap): The Arc gap is distance between the electrode and work piece while the process of EDM takes place. It might be called as spark gap. Spark gap can be handled by servo system (fig no.-1).

(d) Discharge current (current Ip): Current is measured in amp Allowed to per cycle. Discharge current directly alters with the Material removal rate.

(e) Duty cycle (τ): It is a percentage of the on-time relative to the total cycle time. This Parameter is measured by dividing the on-time by the total cycle time (on-time pulse off time).

$$\boldsymbol{\tau} = \frac{T_{on}}{T_{on} + T_{off}}$$

(f) Voltage (V): It is a potential that can be measure as volt, it is also effects the material removal rate and allowed per cycle. Voltage is given as 50 V in this experiment.

(g) Diameter of electrode (D): It is the electrode of Cu-tube there are two different size of diameter 4mm and 6mm in this experiment. This tool is used as electrode and also for internal flushing.

(h) Over cut – It is a clearance per side between the electrode and the work piece after the Machining operation.

1.6 Characteristics of EDM

Specification of EDM by metal removal rate, mechanism of process and other functions as shown in Table 1.

Table 1. Characteristics of EDM

Mechanism of process	Controlled erosion (melting and evaporation) through a series of electric spark
Spark frequency	200 – 500 kHz
Spark gap	0.010- 0.500 mm
Metal removal rate (max.)	5000 mm^3/min
EDM Specific power consumption	2-10 W/mm^3/min
Tool material	Copper, Brass, Graphite, Ag-W alloys, Cu-W alloys.
MRR/TWR	0.1-10
Limitations	High specific energy consumption , non-conducting Materials can't be machined.
Materials that can be machined	All conducting metals and alloys.
Shapes	Micro holes, blind cavities, narrow slots,

1.7 Dielectric Fluid

In EDM, as has been discussed earlier, material removal mainly occurs due to melting and thermal evaporation. As thermal processing is required to be carried out in absence of oxygen so that the process can be controlled and its oxidation is avoided. Often oxidation leads to poor surface conductivity (electrical) of the work piece blocking further machining. Hence, dielectric fluid should provide an oxygen free machining environment and at the same time it should have enough strong dielectric resistance so that electrically it does not breakdown too easily but at the same time ionize when electrons collide with its molecule. Moreover, it should be thermally resistant during sparking as well.

The dielectric fluid and its functions:

(a) It helps in initiating discharge acting as a conducting medium when ionised, and conveys the spark. Its energy is concentrated to a very narrow region.

(b) It helps in cooling the work, quenching the spark, tool electrode and enables arcing to be prevented.

(c) Eroded metal is carried away along with it.

(d) It acts as a coolant while quenching the sparks.

The metal removal rate, electrode wear rate and other operation characteristics are also influenced by the dielectric fluid. The general dielectric fluids used are transformer on silicon oil, kerosene (paraffin oil), EDM oil and de-ionized water are used as dielectric fluid in EDM. Tap water is not used as it gets early ionized and thus breakdown due to presence of salts due to the occurrence of impurities. Dielectric medium is generally passed forcing around the spark zone and also applied through the tool to achieve efficient removal of molten material.

1.8 Flushing Method

Flushing is an important function in any electrical discharge machining operation. It is the process of introducing clean filtered dielectric fluid into the spark gap. There are various types of flushing methods used to remove the metal particles efficiently.

1.9 Tool Material

When it is impinged by positive ions tool material should be such that it would not undergo much tool wear.

Hence electrode materials and its basic characteristics are:

1. High electrical conductivity – since there is less bulk electrons they are cold emitted more easily and electrical heating.

2. High thermal conductivity – for the same heat load, due to faster heat conducted to the bulk of the tool the local temperature rise would be less and thus less tool wear.

3. Higher density – for the same heat load and same tool wear by weight there would be less tool wear or volume removal and thus less dimensional loss or inaccuracy.

4. High melting point – high melting point results in less tool wear due to less tool material melting for the same heat load.

5. Easy manufacturability.

6. Cost – cheap.

The followings are the different electrode materials which are used commonly in the industry:

1. Copper, graphite, Tellurium copper – 99% Cu + 0.5% tellurium and brass.

In this experiment we use the Cu tool.

1.10 Design Variable

Design parameter, constant parameter and process parameter are following ones,

Design parameters are

1. Material removal rate.

2. Tool wear rate

3. over cut (OC)

Machining parameters are

1. Discharge current (Ip)

2. Pulse on time (Ton)

3. Diameter of U-shaped tool

Constant parameters are

1. Duty cycle

2. Voltage

3. Flushing pressure

4. Polarity

1.11Work Piece Material

It is capable of machining hard material components or geometrically complex, that are precise and difficult-to-machine such as heat treated tool steels, super alloys, composites, carbides, ceramics, heat resistant steels etc.

There are different types of tool material are being used in the EDM method. And the tool steel contains alloy and carbon steels that are particularly well-suited to be made into tools. Their suitability comes from their resistance to abrasion, distinctive hardness, their ability to hold a cutting edge firmly, and/or their resistance of getting deformed at elevated temperatures (red-hardness). Steel tool is generally used in a heat-treated state. In general, the edge temperature under expected use is an important determinant of both required heat treatment and composition. The higher carbon grades are typically used for such applications as stamping dies, metal cutting tools etc.

In this experiment EN-18 steel material is used.

1.12 Application of EDM

1. The EDM process is most widely used by the die industries and mould-making tool, but is becoming a common method of making prototype and production parts, especially in the automobile, aerospace and electronics industries in which production quantities are relatively low.

2. It is used to machine extremely hard materials that are difficult to machine like alloys, tungsten carbides, tool steels etc.

3. It is used for forging, wire drawing, extrusion, thread cutting.

4. It is used in drilling of curved holes.

5. For internal thread cutting and helical gear cutting it is used.

6. It is used for machining corners and sharp edges that cannot be machined effectively by other machining processes

7. Higher Tolerance limits can be obtained in this type of machining. Hence areas which require higher surface accuracy use the EDM machining process.

8. By the EDM machining process ceramic materials that are difficult to machine can be machined.

9. Electric Discharge Machining has also made its presence felt in the new fields such as sports, medical and surgical, optical, instruments, including automotive R&D areas.

10. It is a promising technique to meet increasing demands for smaller components usually multi-functional parts and highly complicated that are used in the field of micro-electronics.

1.13 Advantages of EDM

(a) All materials which are electrically conductive can be cut using the EDM process.

(b) Hardened work pieces can be machined, deformation caused by heat treatment can be eliminated.

(c) Using simple electrode X, Y, and Z axes movements allow for the programming of complex profiles.

(d) Complex dies sections and moulds can be produced accurately and faster at lower cost values. These modern NC control systems on die sinking machines are making complicated work pieces yield good results.

(e) Forces are produced by the EDM-process and that, as already mentioned, flushing and hydraulic forces may become large for some work piece geometry. However large cutting forces of the mechanical materials removal processes remain absent.

(f) Without deforming the part thin fragile sections such as webs or fins can be easily machined.

Chapter 2

Literature Review

In this section discussion is done on EDM input parameters such as voltage, current, T_{on}, T_{off}, duty cycle etc. and its impact on output parameters such as material removal rate and surface roughness. Brief paper work done by the researcher's is explained in this section.

- Cao and Yang [1] carried out an experiment, and then they have used artificial neural network (ANN) and genetic algorithm (GA) together to establish the parameter optimization model. An ANN model which adapts Levenberg-Marquardt algorithm has been setup to make an equation between input and output parameters. Output parameters such as surface roughness and Material removal rate are then optimized using Genetic algorithm. This model is shown effective and values obtained are much optimized one.

- Lee et al. [2] have done experiment and found that the results of MRR and surface roughness increases with the values of pulse current but after certain value SR and MRR reduce because of expansion of electric plasma. Surface crack density is affected by pulse current while the crack opening is influenced by the pulse on duration.

- Karthikeyan et al. [3] knowing the importance of AL-SIC particulate composites and their wide spread application from automotive, aircraft to household appliances. However, these materials are hard to machine because of abrasive nature of their composites. Experiment was done on EZNC EDM machine using 20 mm diameter copper electrode. Three level full factorial designs were used and its analysis is done.

- Dewangan and Prabhkar [4] steel is categorized as difficult to machine materials, possess toughness and greater strength are usually known to create major challenges during conventional and non- traditional machining. The Electric discharge machining process is finding out the effect of machining parameter such as I_a (current), T_{on} and diameter of tool of AISI P20 tool steel material. Using U-shaped cu tool with internal flushing. A well-designed experimental scheme was used to reduce the total number of experiments and by Taguchi method results were determined to be effective.

- Joshi and Pande [5] made an intelligent approach for process modelling and optimizing of EDM. Physics based process modelling using finite element method and soft computing techniques such as Genetic algorithm and ANN to improve prediction accuracy of the model. The proposed model (FEM-ANN-GA) is found out to be robust and optimum results are obtained.

- Rajesh and Dev [6] considering the input parameters such as voltage, current, pulse on time, and pulse off time, made an effective optimization model using Response surface methodology and Genetic algorithm technique.

3 Method Adopted in Optimization

3.1Regression Analysis

In statistics, regression analysis is a technique developed statistically for estimating the relationships among variables. It includes many techniques for modelling and analysing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. Most importantly, regression analysis helps one understand how the typical value of the dependent variable changes when any one of the independent variables is varied, with keeping the other independent variables held fixed. Most commonly, regression analysis estimates the conditional expectation of the dependent variable given the independent variables – that is, the average value of the dependent variable when the independent variables are held constant. Less commonly, the focus is on a quintile, or other location parameter which belong to conditional distribution of the dependent variable given the independent variables. In every case, the estimation target is a function of the independent variables called the regression function. The altering of the dependent variable with the regression function, which can be described by a probability distribution.

3.2 Genetic Algorithm Technique

Genetic algorithm possesses advantages that do not require any inherent parallelism and gradient information in searching the design space. Now it is a robust adaptive optimization technique. Some researchers investigated GA application in EDM. Long back used a multi objective optimization method, non-dominating sorting genetic algorithm-II to maximize the result of the process. This provides an optimization model based on genetic algorithms for EDM parameters to imitate a decision. Genetic algorithms find application in bioinformatics, phylogenetic, economics, computational science, engineering, chemistry, manufacturing, pharmacometrics, mathematics, physics and other fields.

Flow chart diagram for Genetic algorithm:

Flow chart diagram for this model is shown in Figure 3.

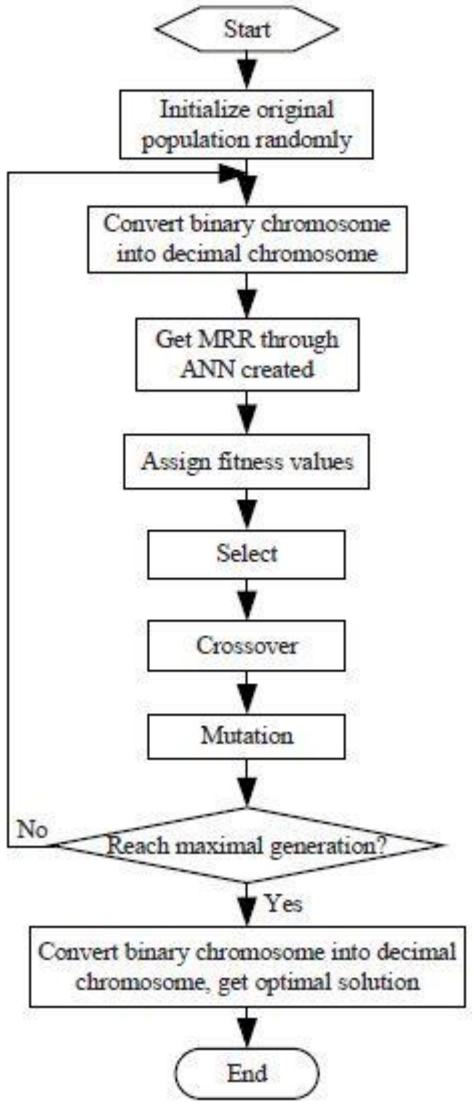


Figure 3. Flowchart diagram of Genetic Algorithm

4. Results

Experimental data is taken by electrical discharge machining of work piece material EN 18 steel and tool is made of copper material. Details are shown in Table 2.

Table 2. MRR and SR Experiment Results

Experiment no	Pulse time I (A)	Pulse time $T_{on\ (\mu\ sec)}$	Duty cycle $T_{au\ (\%)}$	MRR (mm^3 /min)	Surface roughness (µm)
1	1	100	50	0.24221	3.8
2	1	500	65	.21685	7.13
3	1	1000	85	.10205	6.13
4	5	100	50	2.03954	7.4
5	5	500	65	2.00242	8.26
6	5	1000	85	0.89272	7.13
7	9	100	50	5.76275	7.8
8	9	500	65	5.58376	12.67
9	9	1000	85	5.38266	12.33

Estimation of surface roughness and material removal rate for the input parameters of $I_{p,}$ $T_{on,}$ T_{au} is known by the Table 2.

And this experimental data is analysed for their optimum values using mat lab and Minitab software's. Minitab is used for obtaining objective function and Mat lab is used to optimize the objective function using Genetic algorithm.

Mini tab results:

Regression Analysis: MRR versus I_p, T_{on}, T_{au}

The regression equation is

MRR = - 1.27 + 0.674 Ip - 0.000631 Ton + 0.0106 Tau

Coefficients of the equations obtained in mat lab are shown on Table 3 to Table 13.

Table 3. Coefficient, SE Coefficient, T and P values of MRR equation

Predictor	Coefficient	SE Coefficient	T	P
Constant	-1.266	1.409	-0.90	0.410
Ip	0.67367	0.08292	8.12	0.000
Ton	-0.0006311	0.0007356	-0.86	0.430
tau	0.01055	0.01889	0.56	0.600

S = 0.812448   R-Sq = 93.1%   R-Sq(adj) = 88.9%

Analysis of Variance

Table 4. DF, SS, MS, F, P Values of ANOVA Method of MRR

Source	DF	SS	MS	F	P
Regression	3	44.260	14.753	22.35	0.003
Residual Error	5	3.300	0.660	--------	--------
Total	8	47.5600	---------	----------	----------

Table 5. DF, Seq SS Values of MRR

Source	DF	Seq SS
Ip	1	43.568
Ton	1	0.486
Tau	1	0.206

Regression Analysis: SR versus I_p, T_{on}, T_{au}

The regression equation is

$$SR = 4.71 + 0.656\ I_p + 0.00227\ T_{on} - 0.0169\ T_{au}$$

Table 6. Coefficient, SE Coefficient, T and P Values of SR equation

Predictor	Coefficient	SE Coefficient	T	P
Constant	4.708	3.054	1.54	0.184
Ip	0.6558	0.1797	3.65	0.015
Ton	0.002273	0.001594	1.43	0.213
tau	-0.01691	0.04094	-0.41	0.697

S = 1.76094   R-Sq = 75.6%   R-Sq(adj) = 61.0%

Analysis of Variance

Table 7. DF, SS, MS, F, P Values of ANOVA Method of SR

Source	DF	SS	MS	F	P
Regression	3	48.125	16.042	5.17	0.054
Residual Error	5	15.504	3.101	--------	--------
Total	8	63.629	---------	----------	----------

Table 8. DF, Seq SS Values of SR

Source	DF	Seq SS
Ip	1	41.291
Ton	1	6.304
Tau	1	0.529

Nonlinear Regression: SR = alpha * I_p * T_{on} * T_{au}

Method

Algorithm Gauss-Newton

Max iterations 200

Tolerance 0.00001

Starting Values for Parameters

Parameter Value

Alpha 10

Equation

$SR = 2.94937e\text{-}005 * I_p * T_{on} * T_{au}$

Parameter Estimates

Parameter	Estimate	SE Estimate
Alpha	0.0000295	0.0000070

Lack of Fit

There are no replicates.

Minitab couldn't do the lack of fit test by just analysing pure error.

Starting Values for Parameters

Parameter	Value
Cons	10
a1	10
a2	10
a3	10

Equation

$SR = 5.85208 + 0.06452 * I_p \wedge 2 + 1.42607e\text{-}006 * T_{on} \wedge 2 - 0.000146241 * T_{au} \wedge 2$

Parameter Estimates

Table 9. Estimate and SE Estimate Values of SR Nonlinear Regression

Parameter	Estimate	SE Estimate
Cons	5.85208	1.85215
a 1	0.06452	0.01863
a 2	0.00000	0.00000
a 3	-0.00015	0.00032

SR = cons + a1 * I_p ^ 2 + a2 * T_{on} ^ 2 + a3 * T_{au} ^ 2

Lack of Fit

There are no replicates.

Minitab couldn't do the lack of fit test by just analysing pure error.

Summary

Table 10. Final SSE, DSE, MSE and S Values of SR equation

Iterations	2
Final SSE	15.5045
DFE	5
MSE	3.10090
S	1.76094

Regression Analysis: SR versus I_p, T_{on}, T_{au}

The regression equation is SR = 5.15 + 0.639 I_p + 0.00213 T_{on} - 0.0205 T_{au}

Table 11. Final Coefficient, SE Coefficient, T and P values of SR equation Nonlinear Method

Predictor	Coefficient	SE Coefficient	T	P
Constant	5.152	2.985	1.73	0.145

Ip	0.6392	0.1757	3.64	0.015
Ton	0.002131	0.001558	1.37	0.230
tau	-0.02051	0.04002	-0.51	0.630

S = 1.72133 R-Sq = 75.5% R-Sq(adj) = 60.7%

Analysis of Variance

Table 12. Final DF, SS, MS, F, P Values of ANOVA Method of SR

Source	DF	SS	MS	F	P
Regression	3	45.539	15.180	5.12	0.055
Residual Error	5	14.815	2.963	--------	--------
Total	8	60.354	---------	----------	----------

Table 13.DF and Seq SS Values

Source	DF	Seq SS
I_p	1	39.219
T_{on}	1	5.541
T_{au}	1	0.778

4.1. Optimizing by Genetic Algorithm Technique

Objective function for optimized estimation of Material removal rate is

Regression equation for

1) MRR = - 1.27 + 0.674 Ip - 0.000631 Ton + 0.0106 Tau

And this MRR equation has got R-sq value of 93.1%

Though there is lack of fit, being R-sq value 76% equation is taken as

The regression equation is

2) SR = 4.71 + 0.656 Ip + 0.00227 Ton - 0.0169 tau.

These equations are optimized using genetic algorithm in mat lab software tool box

With current iteration 51:

Objective function value: -6.305492566257689

This is the optimized Material removal rate and it is obtained at for the values 9.997, 100.114 and 84.993 of Ip, Ton, Tau respectively.

Max and min boundary conditions are [1, 100, 50] and [10, 1000, 85].

Similarly for Surface roughness:

Objective function value: 4.22814646450867

At the values, 1,100 and 80.766 of I_p, T_{on} and T_{au} respectively.

And the graphs obtained for best fitness of Material removal rate are shown on Figure 4.

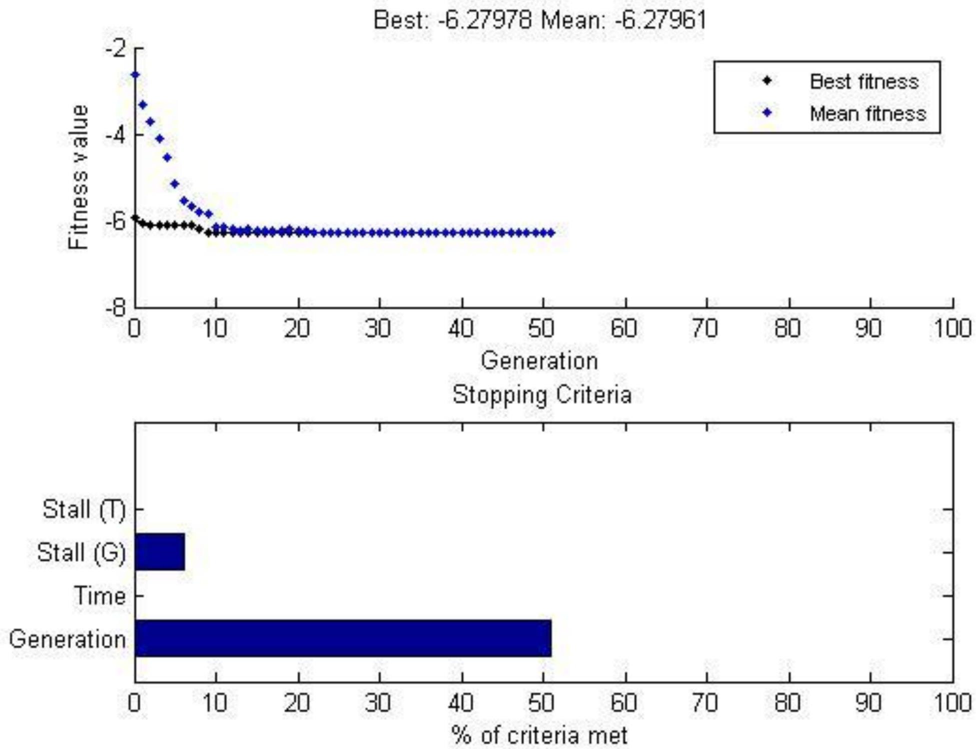


Figure 4. MRR best fitness and stopping criteria graphs

Expectation curve of MRR is shown in Figure 5.

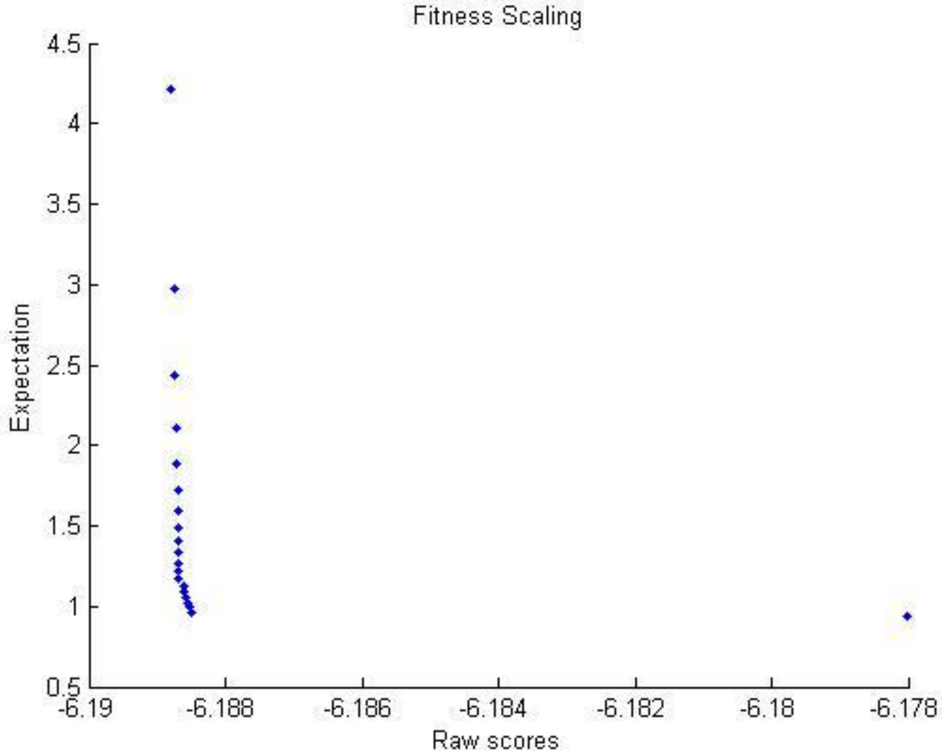


Figure 5. Expectation curve of MRR

And for that of Surface roughness is shown in Figure 6.

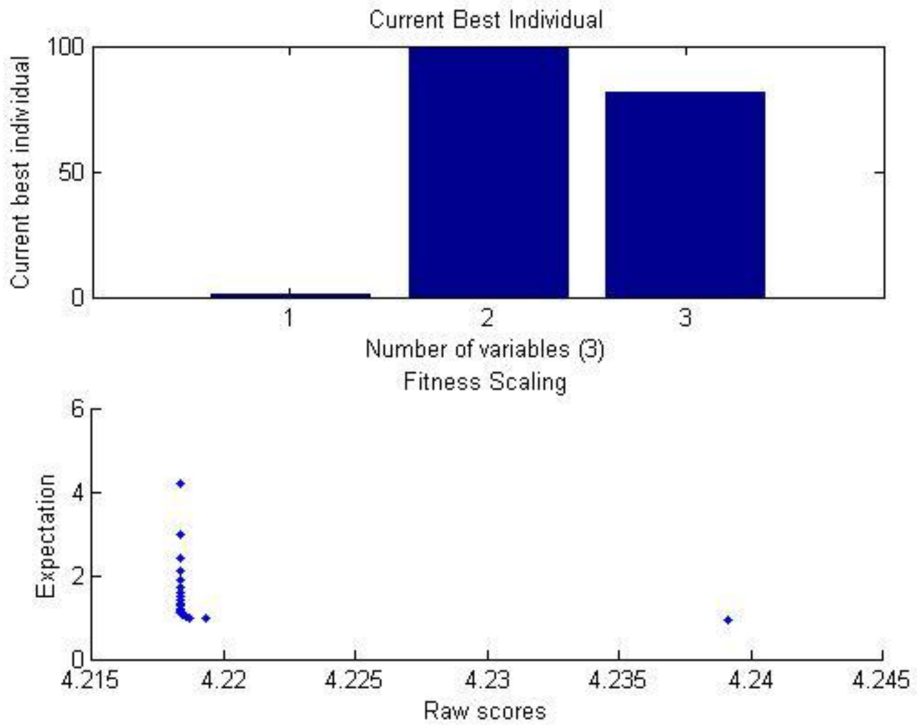


Figure 6. Best current individual and expectation graph of SR

And for best fitness and stopping criteria of SR is shown in Figure 7.

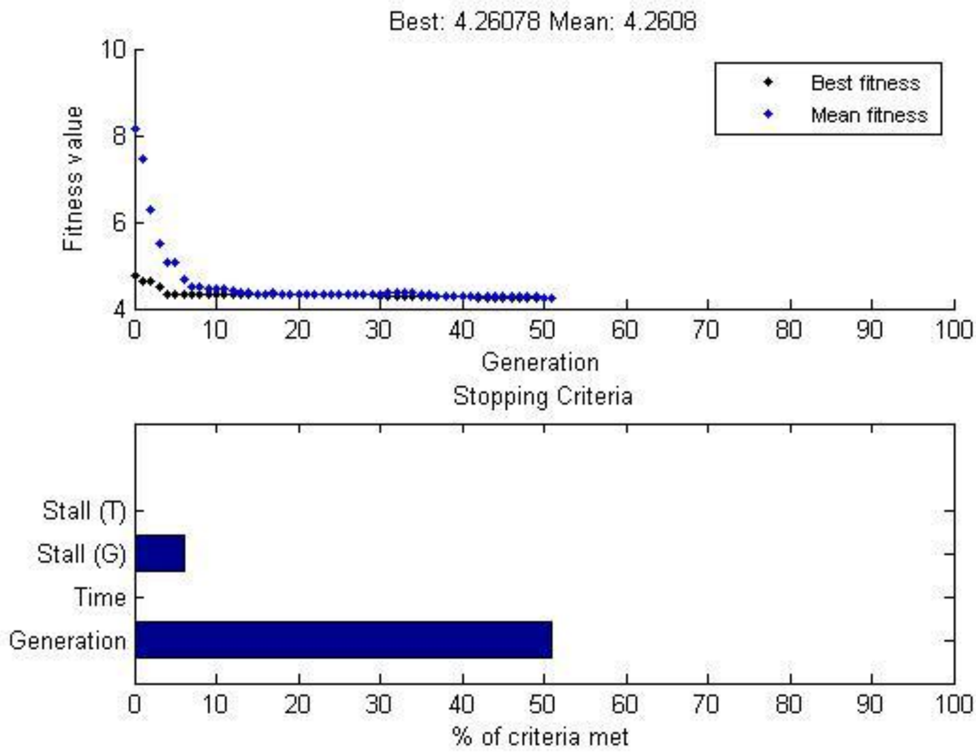


Figure 7. Best fitness and Stopping graphs of SR

5. CONCLUSION

Main objective is to maximize Material removal rate and minimize surface roughness of the work piece and by Genetic Algorithm technique results obtained are:

With terminating current iteration 51:

Objective function value: -6.305492566257689

This is the optimized Material removal rate and it is obtained at for the values 9.997, 100.114 and 84.993 of Ip, Ton, Tau respectively.

Max and min boundary conditions are [1, 100, 50] and [10, 1000, 85].

Similarly for Surface roughness:

Objective function value: 4.22814646450867

At the values 1,100 and 80.766 of Ip, Ton, Tau respectively.

6. REFERENCES

1. Cao, F.G., and Yang, D.Y., 2004, “The study of high efficiency and intelligent optimization system in EDM sinking process,” Journal of Materials Processing Technology, 149(1-3), pp. 83-87.

2. Lee H.T, Hsu F.C., and Tai T.Y., 2004, “Study of surface integrity using the small area EDM process with a Copper-Tungsten electrode,” MATERIAL SCIENCE and ENGINEERING, A364, pp. 346-356.

3. Karthikeyan, R., Lakshmi Narayanan, P.R. and Naagarazan, R.S., 1999, “Mathematical modelling for electric discharge machining of aluminium-silicon carbide particulate composites,” Journal of Materials Processing Technology, 87(1-3), pp. 59-63.

4. Dewangan, S., Datta, S., Patel, S.K., and Mahapatra S.S., 2011, “A case study on quality and productivity optimization in electric discharge machining,” *14 th International Conference in Advanced Materials and Processing Technologies AMPT201113-16 July, Istanbul, Turkey.*

5. Joshi, S, N., and Pande, S.S., 2011, **“**Intelligent process modelling and optimization of die-sinking electric discharge machining,” Elsevier, 11(2), pp. 2743–2755.

6. Mandal, D., Pal, S.K., and Saha, P., 2007, “Modelling of electrical discharge machining process using back propagation neural network and multi-objective optimization using non-dominating sorting genetic algorithm-II,” Journal of Materials Processing Technology, 186(1-3), pp. 154-162.